SOLE INVENTOR

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APPLICATION FOR
UNITED STATES LETTERS PATENT

S P E C I F I C A T I O N

TO ALL WHOM IT MAY CONCERN:

Be it known that I, Jeffrey S. Bartlett a citizen of the United States, residing at 760 Pingree Drive, in the County of Franklin and City/State of Worthington, Ohio 43085 have invented a new and useful AAV2 VECTORS AND METHODS, of which the following is a specification.

AAV2 VECTORS AND METHODS

Related Applications

The present application claims priority benefit of United States Provisional Application No. 60/260,124 filed January 5, 2001 which is herein incorporated by reference in its entirety.

Field of the Invention

The invention relates to Adeno-associated virus vectors. In particular, it relates to Adeno-associated virus vectors with modified capsid proteins and materials and methods for their preparation and use.

Background

Adeno-associated virus (AAV) is a replication-deficient parvovirus, the single-stranded DNA genome of which is about 4.7 kb in length including 145 nucleotide inverted terminal repeat (ITRs). The nucleotide sequence of the AAV serotype 2 (AAV2) genome is presented in Srivastava *et al., J. Virol., 45*: 555-564 (1983) as corrected by Ruffing *et al., J. Gen. Virol., 75*: 3385-3392 (1994). *Cis*-acting sequences directing viral DNA replication (rep), encapsidation/packaging and host cell chromosome integration are contained within the ITRs. Three AAV promoters, p5, p19, and p40 (named for their relative map locations), drive the expression of the two AAV internal open reading frames encoding rep and cap genes. The two rep promoters (p5 and p19), coupled with the differential splicing of the single AAV intron (at nucleotides 2107 and 2227), result in the production of four rep proteins (rep 78, rep 68, rep 52, and rep 40)from the rep gene. Rep proteins possess multiple enzymatic properties which are ultimately responsible for replicating the viral genome. The cap gene is expressed from the p40 promoter and it encodes the three capsid proteins VP1, VP2, and VP3. Alternative splicing and non-consensus translational start sites are responsible for the production of the three related capsid proteins. A single consensus polyadenylation site is located at map position 95 of the

AAV genome. The life cycle and genetics of AAV are reviewed in Muzyczka, *Current Topics in Microbiology and Immunology, 158*: 97-129 (1992).

When AAV infects a human cell, the viral genome can integrate into chromosome 19 resulting in latent infection of the cell. Production of infectious virus does not occur unless the cell is infected with a helper virus (for example, adenovirus or herpesvirus). In the case of adenovirus, genes E1A, E1B, E2A, E4 and VA provide helper functions. Upon infection with a helper virus, the AAV provirus is rescued and amplified, and both AAV and adenovirus are produced.

AAV possesses unique features that make it attractive as a vaccine vector for expressing immunogenic peptides/polypeptides and as a vector for delivering foreign DNA to cells, for example, in gene therapy. AAV infection of cells in culture is noncytopathic, and natural infection of humans and other animals is silent and asymptomatic. Moreover, AAV infects many mammalian cells allowing the possibility of targeting many different tissues *in vivo*. Replication of the viral DNA is not required for integration, and thus helper virus is not required for this process. The AAV proviral genome is infectious as cloned DNA in plasmids which makes construction of recombinant genomes feasible. Furthermore, because the signals directing AAV replication, genome encapsidation and integration are contained within the ITRs of the AAV genome, some or all of the internal approximately 4.3 kb of the genome (encoding replication and structural capsid proteins, rep-cap) may be replaced with foreign DNA such as a gene cassette containing a promoter, a DNA of interest and a polyadenylation signal. The rep and cap proteins may be provided *in trans*. Another significant feature of AAV is that it is an extremely stable and hearty virus. It easily withstands the conditions used to inactivate adenovirus (56° to 65°C for several hours), making cold preservation of rAAV-vectors less critical. AAV may even be lyophilized. Finally, AAV-infected cells are not resistant to superinfection.

Recent research on AAV has therefore involved attempts to modify the viral genome. As the range of cells that AAV will infect is so broad, some researches have focused on modifying the virus so that it targets specific types of cells for infection. The cellular range or tropism of the virus is determined by the binding of AAV capsid protein(s) to receptor and/or coreceptor proteins expressed on the surface of target

cells. Heparin-sulfate proteoglycan (HSPG) is the primary cellular attachment receptor for AAV2. In attempts to enable AAV to bind other cellular receptors, mutagenesis of the AAV capsid-encoding DNA to encode heterologous targeting peptides as part of a capsid protein has produced varying results. For example, Girod *et al.(Nature Medicine, 5*: 1052-1056, 1999) describes AAV2 insertional mutants generated to target L14-specific integrin receptors. These mutant AAV2 vectors expressed capsid proteins which had a fourteen amino acid peptide comprising the RGD domain of the laminin fragment P1 inserted at six different sites. Rabinowitz *et al.* (*Virology, 265*: 274-285, 1999) attempted to identify capsid domains and positions which were capable of tolerating insertions without loss of function. Related PCT application WO 00/28004 describes the modified capsid proteins containing insertions such as melanocyte stimulating hormone, poly-histidine tracts, poly-lysine tracts, an RGD domain and bradykinin. Only a few of the modified capsid proteins could be incorporated into functional viral particles and titers of the viruses were drastically lower than wild-type virus.

Summary of the Invention

The present inventors recognized a need in the art for identification of sites in the AAV capsid protein(s) from which peptides/polypeptides of interest may be presented in a desired conformation to allow the development of AAV vectors that deliver DNA to specific target cells and the development of AAV vectors that present/display on their surface immunogenic peptides/polypeptides. Their invention is based on the elucidation of sites/regions in the AAV2 capsid protein that are amenable to insertion of heterologous peptides, the development of scaffolding sequences required for proper conformation of peptides, and the construction of AAV2 vectors with altered tropism. The full length nucleotide sequence of the wild type AAV2 vector is set out as SEQ ID NO: 12. The amino acid sequence of VP1capsid protein (SEQ ID NO: 13) is encoded by the nucleotides 2203-4410 of SEQ ID NO: 12, the amino acid sequence of VP2 capsid protein (SEQ ID NO: 14) is encoded by nucleotides 2614-4410 of SEQ ID NO: 12 and the amino acid sequence of

VP3 capsid protein (SEQ ID NO: 15) is encoded by nucleotides 2809-4410 of SEQ ID NO: 12.

The present invention provides AAV vectors (viral particles) encoding capsid proteins that comprise insertions of amino acids of interest (*i.e.*, peptides or polypeptides). Preferably, the AAV vectors are AAV2 vectors. Also preferably, DNA encoding the insertions follows the cap gene DNA encoding amino acid position 139 and/or position 161 in the VP1/VP2 capsid region, and/or amino acid position 459, 584, 588 and/or 657 in the VP3 region. While the capsid sites/regions amenable to insertions have been described herein with respect to AAV2, those skilled in the art will understand that corresponding sites in other parvoviruses, both autonomously-replicating parvoviruses and other AAV dependent viruses, are also sites/regions amenable to insertions in those viruses. The amino acids of interest may impart a different binding/targeting ability to the vector or may themselves be immunogenic. As a result, the vectors of the invention exhibit altered characteristics in comparison to wild type AAV, including but not limited to, altered cellular tropism and/or antigenic properties. The invention also contemplates cells, plasmids and viruses which comprise polynucleotides encoding the capsid proteins of the invention.

It is contemplated that in addition to amino acids of interest, amino acids serving as linker/scaffolding sequences as described herein may be included in the AAV vector capsid insert to maintain the functional conformation of the capsid. The linker/scaffolding sequences are short sequences which flank the insertion of interest in the mutated capsid protein. For example, the insertion may have the amino acids TG at its amino terminus and the tripeptide ALS, GLS or LLA at its carboxy terminus.

Techniques to produce AAV vectors, in which a AAV genome to be packaged, rep and cap genes, and helper virus functions are provided to a cell are standard in the art. Production of AAV vectors requires that the following components are present within a single cell (denoted herein as a packaging cell): a rAAV construct consisting of a DNA of interest flanked by AAV inverted terminal repeats, an AAV helper construct containing the capsid gene (which may or may not be comprise an insert) and the rep gene, and an adenovirus helper plasmid or infected with an adenovirus.

The rAAV construct may be delivered to a packaging cell by transfection in a plasmid, infection by a viral genome or may be integrated into the packaging cell genome. The AAV helper construct may be delivered to a packaging cell by transfection of a plasmid or integrated into the packaging cell genome. The adenovirus helper plasmid or adenovirus may be delivered to the packaging cell by transfection/infection. The term "helper virus functions" refers to the functions carried out by the addition of an adenovirus helper plasmid or infection of adenovirus to support production of AAV viral particles.

One method generating a packaging cell with all the necessary components for AAV production is the triple transfection method. In this method a cell such as a 293 cell is transfected with the rAAV construct, the AAV helper construct and a adenovirus helper plasmid or infected with adenovirus. The advantages of the triple transfection method are that it is easily adaptable and straightforward. Generally, this method is used for small scale vector preparations.

Another method of generating a packaging cell is to create a cell line which stably expresses all the necessary components for AAV vector production. For example, a plasmid expressing the rAAV construct, a helper construct expressing the rep and cap proteins (modified or wild type) and a selectable marker, such as Neo, are integrated into the genome of a cell. The packaging cell line is then infected with a helper virus such as adenovirus. The advantages of this method are that the cells are selectable and are suitable for large-scale production of the vector.

In another aspect the invention provides AAV helper constructs encoding a AAV cap gene comprising DNA encoding an insertion of one or more amino acids in the encoded capsid protein(s). The insertion is at a position of the encoded capsid protein(s) that is exposed on the surface of an AAV vector comprising the capsid protein(s) and that does not disrupt conformation of the capsid protein(s) in a manner that prevents assembly of the vector or infectivity of the vector. Limited by these criteria, the size of the insert may vary from as short as two amino acids to as long as amino acids encoding an entire protein. Also provided are cells that stably or transiently produce AAV vectors of the invention. Methods of producing AAV vectors using such cells are contemplated by the invention.

In one embodiment, the AAV vectors of the invention comprising capsid proteins with binding/targeting amino acids inserted are useful for the therapeutic delivery and/or transfer of nucleic acids to animal (including human) cells both *in vitro* and *in vivo*. Nucleic acids of interest include nucleic acids encoding peptides and polypeptides, such as therapeutic (*e.g.*, for medical or veterinary uses) peptides or polypeptides. A therapeutic peptide or polypeptide is one that may prevent or reduce symptoms that result from an absence or defect in a protein in a cell or person. Alternatively, a therapeutic peptide or polypeptide is one that otherwise confers a benefit to a subject, *e.g.*, anti-cancer effects. As a further alternative, the nucleic acid may encode a reporter peptide or protein (*e.g.*, an enzyme). In yet still another alternative, the nucleic acid of interest may be an antisense nucleic acid or a ribozyme.

In another embodiment, the AAV vectors are useful as vaccines. The use of parvoviruses as vaccines is known in the art. Immunogenic amino acids (peptides or polypeptides) may be presented as inserts in the AAV vector capsid. Alternatively, immunogenic amino acids may be expressed from a heterologous nucleic acid introduced into a recombinant AAV genome and carried by the AAV vector. If the immunogenic amino acids are expressed from a recombinant AAV genome, the AAV vector of the invention preferably exhibits an altered cellular tropism and comprises a capsid protein with an insertion of targeting amino acids that are different from those of wild type AAV. Immunogenic amino acids may be from any source (*e.g.*, bacterial, viral or tumor antigens).

AAV vectors of the invention that exhibit an altered cellular tropism may differ from wild type in that the natural tropism of AAV may be reduced or abolished by insertion or substitution of amino acids of interest in a capsid protein of the vector. Alternatively, the insertion or substitution of the amino acids may target the vector to a particular cell type(s) perhaps not targeted by wild type AAV. Cell types of interest contemplated by the invention include, for example, glial cells, airway epithelium cells, hematopoietic progenitors cells and tumor cells. In preferred embodiments, capsid amino acids are modified to remove wild type tropism and to introduce a new tropism. The inserted or substituted amino acid may comprise targeting peptides and polypeptides that are ligands and other peptides that bind to cell

surface receptors and glycoproteins as well as fragments thereof that retain the ability to target vectors to cells. The targeting peptide or polypeptide may be any type of antibody or antigen-binding fragment thereof that recognizes, *e.g.*, a cell-surface epitope. The binding domain from a toxin can be used to target the AAV vector to particular target cells of interest. It is also contemplated that AAV vectors of the invention may be targeted to a cell using a "nonclassical" import/export signal peptide (*e.g.*, fibroblast growth factor-1 and -2, interleukin 1, HIV-1 Tat protein, herpes virus VP22 protein, and the like).

Also contemplated as targeting peptides are peptides that direct uptake of the AAV vector by specific cells. For example, a FVFLP peptide (SEQ ID NO: 18) triggers uptake by liver cells. Another peptide contemplated to direct uptake by cancer cells is the RGD peptide, *e.g.,* 4C-RGD. The RGD domain is known to mediate interactions between extracelluar matrix proteins and integrin receptors located on the surface of cancer cells. It is contemplated that the insertion of an RGD peptide into the capsid of the AAV vector will act as a cell entry mechanism specific to cancer cells. The receptor-binding peptide from luteinizing hormone is also contemplated as a peptide which when inserted into the capsid of an AAV vector will direct entry into ovarian cells since ovarian cells express luteinizing hormone receptors.

Other targeting peptide contemplated influence cellular trafficking of viral particles. Phage display techniques, as well as other techniques known in the art, may be used to identify peptides that recognize, preferably specifically, a cell type of interest. Alternatively, the targeting sequence comprises amino acids that may be used for chemical coupling (*e.g.*, through amino acid side groups of arginine or lysine residues) of the capsid to another molecule that directs entry of the AAV vector into a cell.

The present invention also encompasses modified AAV vectors, the capsid protein(s) of which are biotinylated *in vivo*. For example, the invention contemplates AAV capsids engineered to include the biotin acceptor peptide (BAP). Expression of the *E. coli* enzyme biotin protein ligase during AAV vector biosynthesis in the

presence of biotin results in biotinylation of the AAV capsid proteins as they are made and assembled into viral particles.

In order to biotinylate the AAV viral particles, a system for expressing the biotin ligase enzyme in packaging cell lines is contemplated by the present invention. The invention provides for plasmids, such as the pCMV plasmid, which direct expression of the biotin ligase gene within the packaging cell line. For production of the biotinylated AAV vector the following components need to be transfected into a packaging cell: a rAAV vector comprising DNA of interest flanked by AAV inverted terminal repeats, an AAV helper construct containing a capsid gene with a BAP insert and the rep gene, adenovirus helper plasmid or infected with adenovirus; and the biotin ligase gene (*BirA*). In this system, the biotin ligase gene may be expressed by a plasmid including the *BirA* gene (such as pCMV-BirA) infection with an adenovirus which expresses the *BirA* gene or by using a packaging cell line that is stably transfected with the *BirA* gene.

It is contemplated that the biotinylated AAV viral particles will serve as substrates for conjugation of targeting motifs(*e.g.*, monoclonal antibodies, growth factors, cytokines) to the surface of vector particles through utilizing avidin/strepavidin-biotin chemistry. In addition, the biotinylated AAV viral particles are contemplated to be useful for visualizing the biodistribution of the viral particles both *in vivo* and *in vitro.* The biotinylated viral particles can be visualized with fluorescence or enzymatically with labeled strepavidin compounds. Biotinylation is also useful for conjugating epitope shielding moieties, such as polyethylene glycol, to the AAV vector. The conjugation of shielding moieties allows the vector to evade immune recognition. Biotinylation of the AAV vector is also contemplated to enhance intracellular trafficking of viral particles through conjugation of proteins or peptides such as nuclear transport proteins. Biotinylation may also be used to conjugate proteins or peptides which affect the processing of AAV vector genomes such as increasing the efficiency of integration. In addition, biotinylation may also be used to conjugate proteins or peptides that affect the target cells, *e.g.*, proteins that make a target cell more susceptible to infection or proteins that activate a target cell

thereby making it a better target for the expression of a therapeutic or antigenic peptide.

The present invention also provides compositions comprising an AAV vector of the invention in a pharmaceutically acceptable carrier. The compositions may also comprise other ingredients such as diluents and adjuvants. Acceptable carriers, diluents and adjuvants are nontoxic to recipients and are preferably inert at the dosages and concentrations employed, and include buffers such as phosphate, citrate, or other organic acids; antioxidants such as ascorbic acid; low molecular weight polypeptides; proteins, such as serum albumin, gelatin, or immunoglobulins; hydrophilic polymers such as polyvinylpyrrolidone; amino acids such as glycine, glutamine, asparagine, arginine or lysine; monosaccharides, disaccharides, and other carbohydrates including glucose, mannose, or dextrins; chelating agents such as EDTA; sugar alcohols such as mannitol or sorbitol; salt-forming counterions such as sodium; and/or nonionic surfactants such as Tween, pluronics or polyethylene glycol (PEG).

Methods of eliciting an immune response to amino acids of interest are contemplated by the invention. The methods comprise a step of administering an immunogenic dose of a composition comprising a AAV vector of the invention to a animal (including a human person) in need thereof. In the methods, the immunogenic amino acids may be inserted in the AAV vector capsid protein(s) or may be encoded by a recombinant genome encapsidated as the AAV vector. An immunogenic dose of a composition of the invention is one that generates, after administration, a detectable humoral and/or cellular immune response in comparison to the immune response detectable before administration or in comparison to a standard immune response before administration. The invention contemplates that the immune response resulting from the methods may be protective and/or therapeutic.

Therapeutic methods of delivering and/or transferring nucleic acids of interest to a host cell are also contemplated by the invention. The methods comprise the step of administering a therapeutically effective dose of a composition comprising a AAV vector of the invention to an animal (including a human person) in need thereof. A therapeutically effective dose is a dose sufficient to alleviate (eliminate or reduce) at

least one symptom associated with the disease state being treated. Administration of the therapeutically effective dose of the compositions may be by routes standard in the art, for example, parenteral, intravenous, oral, buccal, nasal, pulmonary, rectal, or vaginal.

Titers of AAV vector to be administered in methods of the invention will vary depending, for example, on the particular virus vector, the mode of administration, the treatment goal, the individual, and the cell type(s) being targeted, and may be determined by methods standard in the art.

Detailed Description

The present invention is illustrated by the following examples that are not intended to limit the invention. Example 1 describes construction of AAV packaging plasmids encoding altered capsid proteins and analysis of the ability of the altered capsid proteins to be assembled into infectious AAV vectors. Example 2 presents assays for the surface expression of epitopes inserted in the altered capsid proteins. Example 3 describes experiments testing whether the AAV vectors retained HSPG-binding ability. Example 4 describes construction and characterization of a mutant AAV vector containing a double insertion within the capsid protein. Example 5 includes analysis of the effect of linker and scaffold sequences on the altered capsid proteins. Example 6 presents the results of experiments in which AAV vectors encoding capsid proteins with an insertion of an luteinizing hormone receptor binding peptide were able to transduce OVCAR-3 cells. Example 6 also discusses various indications amenable to use of AAV vectors of the invention. Example 7 and 8 describe fourteen additional modified AAV vectors, wherein the RGD-4C peptide motif was inserted into the capsid proteins. The experiments described in Example 9 demonstrate that the AAV-RGD vectors attach to and enter cells via integrin receptors. Example 10 demonstrates that the AAV-RGD vectors were capable of mediating gene delivery via integrin receptors. Example 11 demonstrates that the AAV-RGD vectors transferred genes to ovarian adenocarcinoma cell lines. Example 12 describes AAV mediated eGFP gene delivery to human ovarian tumor xenografts established in SCID mice. Example 13 describes construction of mutant AAV vectors

which are biotinylated *in vivo* through an insertion of the biotin acceptor peptide in the capsid protein. Finally, Example 14 describes a packaging system for biotinylated AAV vectors.

Example 1

In order to identify sites within the AAV2 capsid that could tolerate insertion of targeting epitopes, an extensive site-specific mutagenesis strategy was designed. Regions of the AAV2 capsid DNA to be modified were chosen by analyzing data from a number of sources to predict which ones encoded capsid amino acids that were exposed on the surface of the virion and which encoded amino acids that could be replaced with other amino acids without significantly altering the conformation of the rest of the capsid protein(s). One source of data was a comparison of structural information from five related autonomous parvoviruses. The five parvoviruses had solved virion structures and included canine parvovirus (CPV)(Tsao *et al., Science, 251*: 1456-1464 and Wu *et al., J. Mol. Biol., 233*: 231-244), feline panleukopenia virus (FPV)(Agbandje *et al., Proteins, 16*: 155-171), minute virus of mice (MVM)(Agbandje-McKenna *et al., Structure, 6*: 1369-1381 and Llamas-Saiz *et al., Acta Crystallogr. Sect. D. Biol. Crystallogr., 53*: 93-102), parvovirus B19 (B19)(Chipman *et al., Proc. Natl. Acad. Sci. USA, 93*: 7502-7506) and Aleutian mink disease parvovirus (ADV)(McKenna *et al., J. Virol., 73*: 6882-6891). This information was compared to a computer-predicted secondary structure of the AAV2 capsid based on its known primary amino acid sequence. Other sources of data were previous reports of immunogenic regions of the AAV2 capsid and previous reports of effects of random capsid mutations. Finally, the AAV2 capsid primary amino acid sequence was compared with that of other AAV and other parvoviridae for regions of defined secondary structure to create a model of the AAV2 capsid. From the model sites for insertion of small peptides two to fifteen amino acids in length were chosen. A series of thirty-eight virus mutants containing peptide insertions at twenty-five unique sites within the AAV2 capsid protein was generated. Most of the insertions were within the VP1 capsid protein (19/25), four were within the VP1 unique region and two were within the VP1/VP2 unique region. Epitopes inserted within the VP3

protein are expected to be displayed on every capsid monomer within the AAV virion (60/virion). Insertions within the VP1 or VP1/VP2 unique regions would be expected to be displayed three and six times, respectively, per virion.

Site-directed mutagenesis was performed on plasmid pUC-Cap (a subclone of the AAV2 Rep and Cap open reading frames (ORF)). Mutagenesis was confirmed by restriction endonuclease digestion. The altered Cap genes were then substituted for the wild-type AAV2 sequences in plasmid pACG2 to generate the series of mutant helper plasmids described in Table 1 below, wherein epitope AgeI is the amino acids encoded by an AgeI restriction site, epitope NgoMI is the amino acids encoded by an NgoMI restriction site, epitope 4C-RGD is a cyclic RGD-based peptide (CDCRGDCFC; SEQ ID NO: 10) that has been shown to bind a number of integrins, including $\alpha_v\beta_3$, $\alpha_v\beta_5$, $\alpha_5\beta_1$, $\alpha_5\beta_1$, $\alpha_3\beta_1$, $\alpha_2\beta_1$ and $\alpha_6\beta_1$, present on the surface of mammalian cells that is useful for targeting to tumor endothelium and other cell types, epitope BPV is a peptide from bovine papilloma virus (TPPYLK; SEQ ID NO: 16), and epitope LH is a receptor-binding peptide from luteinizing hormone (HCSTCYYHKS; SEQ ID NO: 17). Plasmid nomenclature in the Table 1 can be understood by reference to plasmid pACG-A139 wherein pACG refers to the starting plasmid in which mutant cap sequences were inserted and A139 refers to insertion of an AgeI restriction site after position 139 of the capsid, and by reference to plasmid pACG-A139BPV/GLS wherein BPV indicates the peptide of interest that is inserted and /GLS indicates inclusion of linker amino acids at the carboxy terminus of the inserted epitope.

Table 1

Mutant AAV Packaging Plasmids

Mutant Plasmid Designation	*Location*	*Insertion (epitope)*
pACG-A26	VP1	TG (Age I)
pACG-A46	VP1	TG (Age I)
pACG-A115-4C-RGD/GLS	VP1	TGCDCRGDCFCGLS (SEQ ID NO: 1) (4C-RGD)
pACG-A120	VP1	TG (Age I)
pACG-A139	VP2	TG (Age I)
pACG-A139BPV/GLS	VP2	TGTPFYLKGLS (SEQ ID NO: 2) (BPV)
pACG-A139LH/GLS	VP2	TGHCSTCYYHKSGLS (SEQ ID NO: 3) (LH)
pACG-A161BPV/ALS	VP2	TGTPFYLKALS (SEQ ID NO: 4) (BPV)
pACG-A161BPV/LLA	VP2	TGTPFYLKLLA (SEQ ID NO: 5) (BPV)
pACG-A161BPV/GLS	VP2	TGTPFYLKGLS (SEQ ID NO: 2) (BPV)
pACG-A161LH/GLS	VP2	TGHCSTCYYHKSGLS (SEQ ID NO: 3) (LH)
pACG-A312	VP3	TG (Age I)
pACG-N319	VP3	AG (NgoMI)
pACG-A323-4C-RGD/GLS	VP3	TGCDCRGDCFCGLS (SEQ ID NO: 1) (4C-RGD)
pACG-A339BPV	VP3	TGTPFYLK (SEQ ID NO: 6) (BPV
pACG-A375BPV	VP3	TGTPFYLK (SEQ ID NO: 6) (BPV)
pACG-A441	VP3	TG (Age I)
pACG-A459	VP3	TG (Age I)
pACG-A459BPV/GLS	VP3	TGTPFYLKGLS (SEQ ID NO: 2) (BPV)

Mutant Plasmid Designation	*Location*	*Insertion (epitope)*
pACG-A459LH/GLS	VP3	TGHCSTCYYHKSGLS (SEQ IS NO: 3) (LH)
pACG-A466	VP3	TG (Age I)
pACG-A480-4C-RGD/GLS	VP3	TGCDCRGDCFCGLS (SEQ ID NO: 1) (4C-RGD)
pACG-N496	VP3	AG (NgoMI)
pACG-A520LH/GLS	VP3	TGHCSTCYYHKSGLS (SEQ ID NO: 3) (LH)
pACG-A520BPV/LLA	VP3	TGTPFYLKLLA (SEQ ID NO: 5) (BPV)
pACG-A540	VP3	TG (Age I)
pACG-N549	VP3	AG (NgoMI)
pACG-N584	VP3	AG (NgoMI)
pACG-A584BPV/ALS	VP3	TGTPFYLKALS (SEQ ID NO: 4) (BPV)
pACG-A584BPV/LLA	VP3	TGTPFYLKLLA (SEQ ID NO: 5) (BPV)
pACG-A584BPV/GLS	VP3	TGTPFYLKGLS (SEQ ID NO: 2) (BPV)
pACG-N472	VP3	AG (NgoMI)
pACG-A587BPV/ALS	VP3	TGTPFYLKALS (SEQ ID NO: 4) (BPV)
pACG-A587BPV/LLA	VP3	TGTPFYLKLLA (SEQ ID NO: 5) (BPV)
pACG-A587BPV/GLS	VP3	TGTPFYLKGLS (SEQ ID NO: 2) (BPV)
pACG-A595-4C-RGD/GLS	VP3	TGCDCRGDCFCGLS (SEQ ID NO: 1) (4C-RGD)
pACG-A597-4C-RGD/GLS	VP3	TGCDCRGDCFCGLS (SEQ ID NO: 1) (4C-RGD)
pACG-A657	VP3	TG (Age I)

The mutant AAV packaging plasmids were tested for their ability to generate AAV vectors with altered capsids by triple transfection with plasmid pAAV-LacZ (a plasmid containing LacZ flanked by AAV ITRs) and pXX6-80 (a plasmid containing Adenovirus helper DNA) according to established procedures. AAV vector preparations were assessed for particle formation and vector infectivity. Particles were identified by ELISA using A20 monoclonal antibody, whereas DNA-containing particles were identified by dot-blot and/or PCR. Vector particles were tested for infectivity by cellular transduction assay on Adenovirus-infected C12 cells. Capsid mutants were grouped into three types. Capsid mutants that did not give rise to any viral particles were classified as Type I (7/38). Mutants that produced non-infectious particles were classified as Type II (11/38) and mutants that produced fully infectious viral particles were classified as Type III (20/38). See Table 2 below wherein the actual titers are listed as values for comparison with the wild type titer unless the titer (-) is four orders of magnitude or more less than wild type vector and a titer (+) is below the sensitivity of DNA dot blot but detectable by PCR.

Table 2

Mutant AAV Vector Characterization

	Particle titer			
Mutant Vector Designation	*Dot-blot*	*A20 ELISA*	*Infections titer*	*Mutant Type*
AAV-A26	(+)	7.5 X 10^7	-	II
AAV-A46	9.2 X 10^7	8.0 X 10^7	1.2 X 10^3	III
AAV-A115-4C-RGD/GLS	5.6 X 10^7	7.5 X 10^7	1.2 X 10^2	III
AAV-A120	3.4 X 10^7	8.0 X 10^7	1.0 X 10^3	III
AAV-A139	2.0 X 10^7	9.0 X 10^7	5.0 X 10^5	III
AAV-A139BPV/GLS	1.4 X 10^8	9.0 X 10^7	6.8 X 10^5	III
AAV-A139LH/GLS	1.2 X 10^8	8.0 X 10^7	3.3 X 10^5	III
AAV-A161BPV/ALS	4.0 X 10^7	8.0 X 10^7	1.2 X 10^5	III
AAV-A161BPV/LLA	1.4 X 10^6	7.5 X 10^5	5.9 X 10^2	III
AAV-A161BPV/GLS	1.2 X 10^7	7.5 X 10^6	8.7 X 10^4	III
AAV-A161LH/GLS	4.0 X 10^6	8.0 X 10^7	3.4 X 10^4	III
AAV-A312	1.8 X 10^6	-	5.3 X 10^2	III
AAV-N319	2.4 X 10^7	4.5 X 10^5	0.6 X 10^3	III
AAV-A323-4C-RGD/GLS	(+)	-	-	I
AAV-A339BPV	(+)	-	-	II
AAV-A375BPV	-	-	-	I
AAV-A441	-	-	-	I
AAV-A459	7.2 X 10^6	8.0 X 10^7	6.5 X 10^4	III
AAV-A459BPV/GLS	5.6 X 10^7	4.5 X 10^6	2.2 X 10^5	III
AAV-A459LH/GLS	3.2 X 10^6	4.5 X 10^5	-	II
AAV-A466	(+)	7.5 X 10^7	-	II
AAV-N472	-	-	-	I

Mutant Vector Designation	*Dot-blot*	*A20 ELISA*	*Infections titer*	*Mutant Type*
AAV-A480-4C-RGD/GLS	-	-	-	I
AAV-N496	2.2×10^6	-	1.1×10^2	III
AAV-A520LH/GLS	(+)	7.5×10^7	-	II
AAV-A520BPV/LLA	(+)	7.5×10^7	-	II
AAV-N540	(+)	8.0×10^7	-	II
AAV-N549	(+)	4.5×10^6	-	II
AAV-N584	1.1×10^8	8.0×10^7	4.0×10^5	III
AAV-A584BPV/ALS	3.0×10^7	8.0×10^7	6.5×10^2	III
AAV-A584BPV/LLA	1.3×10^7	9.0×10^6	-	II
AAV-A584BPV/GLS	(+)	7.5×10^5	-	II
AAV-A587BPV/ALS	1.8×10^7	8.0×10^6	5.0×10^1	III
AAV-A587BPV/LLA	7.2×10^5	9.0×10^5	-	II
AAV-A587BPV/GLS	3.5×10^7	9.0×10^7	2.7×10^2	III
AAV-A595-4C-RGD/GLS	-	2.5×10^4	-	I
AAV-A597-4C-RGD/GLS	-	2.5×10^4	-	I
AAV-A657	1.8×10^7	7.5×10^7	5.2×10^4	III
AAV (wild-type)	4.8×10^7	9.0×10^7	6.2×10^5	N/A

Of the sites chosen for linker insertion, 20 (80%) tolerated this manipulation as assessed by particle formation. Infectious virus could be produced containing linker insertions at twelve of the sites that were tolerated for viral assembly (12/20; 60%). This represents 48% of the sites originally selected for mutagenesis.

Although twelve sites within the AAV2 capsid protein(s) could be altered, and the mutant capsid monomers still assemble, package viral genomes, and infect cells, the infectious titers of these viruses varied greatly. These ranged from essentially

wild-type levels to greater than four orders of magnitude less infectious than wild-type. Significantly, several sites could tolerate a wide range of genetic insertions without effects on virus titer. Both of the sites within the VP1/VP2 unique region of the capsid ORF proved able to tolerate genetic insertions without a loss in viral titer. See results for mutant vectors with insertions after amino acid positions A139 and A161. However, insertion after position A161 showed some dependence on surrounding sequence elements. See Example 5 below. Within the VP3 region of the capsid ORF, results were more variable. Although many insertions were tolerated with essentially no loss in vector titer (for example, after positions R459 and Q584), there was a greater dependence on linker sequences (compare AAV-N584BPV/ALS to AAV-N584BPV/LLA; also see Example 5, below) and the primary sequence of the epitope being inserted (compare AAV-A459BPV/GLS to AAV-A459LH/GLS).

Example 2

The surface accessibility of inserted BPV epitopes in the mutant AAV vectors described in Example 1 was examined by immunoprecipitation.

Iodixanol grandient-purified vectors were precipitated with anti-BPV monoclonal antibody using protein-G Sepharose, subjected to SDS-PAGE, blotted to nylon membranes and probed with anti-AAV B1 monoclonal antibody. A summary of epitope display for each BPV insertion mutant is shown in Table 3 below.

Table 3

Surface Display of Inserted BPV Epitopes

Mutant Vector Designation	*Epitope Display*
AAV-A139BPV/GLS	+
AAV-A161BPV/ALS	+
AAV-A161BPV/LLA	+
AAV-A161BPV/GLS	+
AAV-A339BPV	-
AAV-A459BPV/GLS	+
AAV-A520BPV/LLA	+
AAV-A584BPV/ALS	+
AAV-A584BPV/LLA	+
AAV-A584BPV/GLS	-
AAV-A587BPV/ALS	+
AAV-A587BPV/LLA	-
AAV-A587BPV/GLS	+

Inserted peptide epitopes could be displayed efficiently on the surface of viral particles at each site tested which were all sites that insertion gave rise to infectious vectors. However, display was often dependent on inclusion of appropriate linker/scaffolding sequences.

Example 3

The mutant AAV vectors of Example 1 were also tested for retention of the ability to bind HSPG.

The ability of the AAV vectors to bind HSPG was assessed by purifying the AAV preparations on an iodixanol gradient. The 40% iodixanol layer was collected and diluted in PBS-MK containing heparin sulfate affinity resin. The mixtures were incubated for two hours with gentle shaking at 4°C followed by centrifugation. The viral bound resin was washed three times with PBS-MK for ten minutes at room

temperature and resuspended in loading buffer. The samples were then boiled and analyzed by Western blotting with monoclonal antibody B1 directed against the AAV2 VP3 capsid protein.. A summary of the HS-binding characteristic for all of the mutant is presented in Table 4 below.

Table 4

HSPG Binding

Mutant Vector Designation	*HSPG Binding*
AAV-A26	-
AAV-A46	+
AAV-A115-4C-RGD/GLS	+
AAV-A139	+
AAV-A139BPV/GLS	+
AAV-A139LH/GLS	+
AAV-A161BPV/ALS	+
AAV-A161LH/GLS	+
AAV-A312	-
AAV-A323-4C-RGD/GLS	-
AAV-A375BPV	+
AAV-A459	+
AAV-A459LH/GLS	+
AAV-A466	+
AAV-N472	+
AAV-A480-4C-RGD/GLS	+
AAV-A520LH/GLS	-
AAV-A520BPV/LLA	-
AAV-A540	+
AAV-N549	-
AAV-A584BPV/ALS	+

Mutant Vector Designation	*HSPG Binding*
AAV-A584BPV/LLA	+
AAV-A584BPV/GLS	-
AAV-A587BPV/ALS	+
AAV-A587BPV/LLA	+
AAV-A587BPV/GLS	+
AAV-A595-4C-RGD/GLS	+
AAV-A597-4C-RGD/GLS	+
AAV (wild-type)	+

Some of the Type II mutants may have been non-infectious because they no longer bound HSPG (see the A26 or A520 mutants). These mutants are valuable because the endogenous tropism of the virus has been ablated and any binding capability added to the virus would be exclusive. In situations in which loss of receptor-binding ability as a result of introducing mutations at a specific capsid site is not desirable, the foregoing data demonstrates that binding can often be rescued by inclusion of appropriate flexible linker sequences.

Example 4

A mutant AAV2 vectors containing a peptide insertion at two different sites within the capsid protein was generated using the methods described herein. The 4C-RGD peptide (SEQ ID NO: 10) was inserted using site directed mutagenesis as described in Example 1 after amino acid position 520 and position 588 within the VP3 capsid protein. The double mutant AAV2 vector (denoted herein as A520RGD4C588RGD4C) was assessed for particle formation and vector infectivity. Particles were identified by ELISA using A20 monoclonal antibody, whereas DNA-containing particles were identified by dot-blot. Vector particles were tested for infectivity by cellular tranduction assay on Adenovirus-infected C12 cells. The double mutant was able to infect cells and produce viral particles at a similar rate as other mutant and wild-type vectors. In Table 5, infectivity is presented as the percentage of target cells expressing the vector-encoded transgene and particle titer is presented as particles/μl.

Table 5

Capsid	Infectivity	HS Binding	Particle Titer	
			A20 ELISA	DNA Dot Blot
A520RGD4C	-	-	7.5 x 10^4	-
A588RGD4C	52.1%	+	7 x 10^5	8 x 10^4
A520RGD4C588RGD4C	45.8%	-	2 x 10^5	5 x 10^4
ACG	49.9%	+	1 x 10^6	2 x10^5

The ability of the double mutant AAV capsids to bind HSPG was assessed as describe in Example 3. The double mutant was unable to bind to HSPG like the A520RGD4C vector, but retained the ability to infect the target cells similar to A5884RGD4C. See Table 9 above. Thus, the double mutant, A520RGD4C588RGD4C, is a receptor-targeted mutant that was produced at a reasonable titer and is defective in binding the AAV2 endogenous receptor HSPG.

Example 5

It was envisioned that insertion of larger peptide epitopes might disrupt the AAV capsid by conformationally straining neighboring sequences. To circumvent this problem, two different approaches were employed in generating various mutant AAV packaging plasmids described in Example 1. First, in some altered capsids the structure of neighboring capsid regions was maintained by the introduction of a disulfide bond, and second, in other altered capsids flexible linker sequences were included to minimize conformational stress. See Table 6 below, wherein linker sequence TG-ALS indicates that linker amino acids TG were included at the amino terminus of the inserted epitope and amino acids ALS were included at the carboxy terminus of the inserted epitope.

Table 6

Dependence on Appropriate Linker/Scaffolding Sequences

Mutant Vector Designation	*Linker Sequence*	*Particle Titer*	*Infectious Titer*	*HSPG Binding*	*Epitope Display*	*Type*
AAV-A161BPV/ALS	TG-ALS (SEQ ID NO: 7)	++++	++++	+	+	III
AAV-A161BPV/LLA	TG-LLA (SEQ ID NO: 8)	++	++	+	+	III
AAV-A161BPV/GLS	TG-GLS (SEQ ID NO: 9)	+++	++++	+	+	III
AAV-N584BPV/ALS	TG-ALS (SEQ ID NO: 7)	++++	++++	+	+	III
AAV-N584BPV/LLA	TG-LLA (SEQ ID NO: 8)	+++	-	+	+	II
AAV-N584BPV/GLS	TG-GLS (SEQ ID NO: 9)	+	-	-	-	II
AAV-A587BPV/ALS	TG-ALS (SEQ ID NO: 7)	+++	+++	+	+	III
AAV-A587BPV/LLA	TG-LLA (SEQ ID NO: 8)	++	-	+	-	II
AAV-A587BPV/GLS	TG-GLS (SEQ ID NO: 9)	++++	++	+	+	III

Through the choice of appropriate linkers, infectious virus was rescued from previously dead mutants. In other instances, titers were influenced over several orders of magnitude. From this analysis it is clear that incorporation of flexible linkers

containing small uncharged amino acids (such as alanine or serine) is extremely important for rescuing virus structure, infectivity, and for efficient epitope display.

Example 6

The ability of vector AAV-A139LH (containing the LH receptor binding peptide) to target the human ovarian cancer cell line OVCAR-3 was tested. Expression of the LH receptor is upregulated on these cells. Because OVCAR-3 cells also express HSPG control experiments were performed to demonstrate that the AAV vector indeed exhibited an altered tropism.

Briefly, equal numbers of AAV-A139LH vector particles or vector particles with BPV inserts instead of LH inserts were applied to the surface of OVCAR-3 cells for 2 hours at 4°C. HeLa cells which express HSPG but not the LH receptor were used as a control cell line. Experiments were performed either in the presence or absence of 500 μg/ml soluble heparin sulfate (HS) which competes with binding between AAV and HSPG and in the presence or absence of progesterone which increases expression of the LH receptor. The cells were then washed of unbound vector, shifted to 37°C and maintained for 48 hours at which time gene transfer was assessed.

In the experiments, AAV-A139LH transduced both HeLa and OVCAR-3 cells in the absence of HS. In the presence of HS, transduction of OVCAR-3 cells was reduced more than 10-fold and transduction of Hela cells was reduced more than 100-fold. Addition of progesterone restored transduction of ovarian cells that was lost in the presence of HS. The addition of progesterone increased transduction of OVCAR-3 cells by AAV-A139LH but not by AAV-A139BPV.

These results demonstrate that AAV-A139LH has acquired tropism for cells expressing the LH receptor.

As demonstrated by the foregoing data, AAV vectors of the invention may therefore be used for targeted DNA delivery. Some indications include: cancer gene therapy (*e.g.*, for toxin or "suicide" gene delivery) and therapeutic gene transfer to cell and/or tissue types that have been refractive to gene transfer with conventional AAV vectors (*e.g.*, airway epithelium for the treatment of cystic fibrosis, glia for the treatment of primary brain cancers, and hematopoietic progenitors cells for the

treatment of any number of other disorders). For therapeutic gene delivery, AAV vectors of the invention may be targeted to non-antigen presenting cells in order to avoid an immune response to a gene or protein of interest and/or may incorporate epitope shielding moieties and/or mutations of immunodominant epitopes.

Alternatively, AAV vectors may be used as vaccines. Viral particles containing foreign epitopes may be used directly as immunogns. AAV vectors displaying such epitopes may also contain DNA that would lead to the expression of the same or related sequences within target cells. Such a dual immunization approach is contemplated to generate a more robust and wider range response. For vaccine use, targeted AAV vectors may specifically transduce APC (while avoiding other cells).

Finally, AAV vectors of the invention may be used as non-therapeutic reagents such as imaging reagents for the determination of vector pharmokinetics and biodistribution, for example, through the attachment of radio tracer elements and real-time scintography.

Example 7

Fourteen additional AAV capsid mutants were generated in the non-infectious AAV plasmid, pACG, by PCR-based site-directed mutagenesis as described in Example 1. In all thirteen, the 4C-RGD peptide (CDCRGDCFC; SEQ ID NO: 10) was inserted into the AAV capsid monomer.

4C-RGD encoding oligonucleotide were inserted into seven different sites within the AAV capsid gene. One site was within the VP1 unique region of the AAV2 capsid protein gene, three were within the VP1/VP2 unique region, and the three remaining sites were located within the VP3 region of the capsid ORF. DNA encoding the 4C-RGD peptide epitope was either inserted alone or flanked by one of two different five amino acid connecting peptide linkers, as described in Example 5. See Table 7 below. Producer cell lines based on 293 cells were used to generate modified AAV vectors comprising the altered capsids. These modified vectors are denoted as "AAV-RGD" collectively herein.

Table 7

Vector Designation	Upstream Linker	Inserted Peptide (SEQ ID NO: 10)	Downstream Linker	Particle Titer (ELISA)
A46-RGD4C	TG	CDCRGDCFC	-	8.5×10^7
A46-RGD4CGLS	TG	CDCRGDCFC	GLS	4.5×10^6
A115-RGD4C	TG	CDCRGDCFC	-	4.5×10^6
A115 - RGD4CGLS	TG	CDCRGDCFC	GLS	6.0×10^7
A139-RGD4C	TG	CDCRGDCFC	-	8.5×10^7
A139-RGD4CGLS	TG	CDCRGDCFC	GLS	9.0×10^7
A161-RGD4C	TG	CDCRGDCFC	-	4.5×10^6
A161-RGD4CALS	TG	CDCRGDCFC	ALS	5.0×10^6
A459-RGD4C	TG	CDCRGDCFC	-	4.5×10^6
A459-RGD4CGLS	TG	CDCRGDCFC	GLS	4.5×10^6
A584-RGD4C	TG	CDCRGDCFC	-	8.5×10^7
A584-RGD4CALS	TG	CDCRGDCFC	ALS	9.0×10^7
A588-RGD4C	TG	CDCRGDCFC	-	9.0×10^7
A588-RGD4CGLS	TG	CDCRGDCFC	GLS	9.0×10^7
Wild-type	-	-	-	7.5×10^7

All the mutant capsid proteins were efficiently assembled and packaged. Furthermore, all of the modified AAV vectors generated were infectious, although there were significant differences in their efficiency of mediating gene transduction. See Table 8 below.

Table 8

Capsid	Percent eGFP Positive Cells	
	rAVVeGFP (alone)	rAVVeGFP (+ 500 μg/ml Heparin Sulfate)
A46-RGD4C	2.5%	1%
A46-RGD4CGLS	3.%	0.5%
A115-RGD4C	5%	1%
A115 -RGD4CGLS	7.5%	1%
A139-RGD4C	35%	2.5%
A139-RGD4CGLS	40%	2%
A161-RGD4C	4%	0.5%
A161-RGD4CALS	5%	1%
A459-RGD4C	3.5%	1%
A459-RGD4CGLS	3%	0.25%
A584-RGD4C	49%	30%
A584-RGD4CALS	51%	37%
A588-RGD4C	40%	32%
A588-RGD4CGLS	46%	38%
Wild-type	47.5%	1%

The differences in gene transduction among the AAV-RGD vectors were related to both the site of peptide insertion and the presence, or absence, of linker sequences flanking the inserted 4C-RGD peptide. Insertion of the RGD epitope following AAV VP1 amino acids at positions 46, 115, 161 or 459 severely diminished infectious titer. However, insertions following the AAV amino acids at positions 139, 584 and 588 were well tolerated and did not affect titer appreciably.

For all the AAV-RGD vectors, inclusion of linker/scaffolding sequences resulted in slightly more efficient infection and maintenance of titer. To determine if the inserted 4C-RGD peptide had imparted to the modified vectors HSPG-

independence, gene transduction assays were performed in the presence of heparin sulfate as described in Example 5. Although, AAV vectors containing unmodified capsids were unable to transduce cells in the presence of heparin sulfate, AAV-RGD vectors containing the 4C-RGD epitope following amino acids 584 and 588 transduced all types of cells tested in the presence of heparin sulfate. These results strongly suggest that AAV-RGD vectors set out in Table 6 are infecting cells via a HSPG-independent mechanism..

Example 8

To assess if the AAV-RGD viral particles bind integrin receptors, a solid-phase ELISA assay using purified $\alpha_v\beta_3$ integrin was carried out as follows.

Neutravidin-coated plates (Pierce, Rockford, IL) were incubated with 1µg/well of biotinylated heparin in PBST (0.05% Tween 20, 0.2% BSA) overnight at 4°C. The wells were then washed five times with wash buffer (PBS containing 0.05% Tween 20 and 0.1% BSA) and AAV particles were bound at room temperature for two hours with gentle shaking. Subsequently, the plate was washed five times with wash buffer and purified integrin $\alpha_v\beta_3$ (Chemicon, Temecula, CA) in binding buffer (20 mM Tris-HCl, 150 mM NaCl, 2mM $CaCl_2$. 1 mM $MgCl_2$, 1 mM MnCL2 and 0.1% BSA, pH 7.5) was added to each well at a concentration of 1µg/ml. The plates were incubated overnight at 4°C, washed three times with wash buffer and incubated with VNR139 monoclonal antibody (anti-α_v subunit, GIBCO-BRL; Gaithersburg, MD) in binding buffer for 2 hours at room temperature. The plates are then washed five times and incubated with secondary antibody (HRP-conjugated anti-mouse IgG) for 1 hour at room temperature. Following a final wash the ELISA plate was developed with ABTS substrate solution and the VECTASTAIN kit (Vector Laboratories, Burlingame, CA) as recommended by the manufacturer. Color development was stopped by the addition of 1N H_2SO_4, and plates were read in a plate reader set at 405 nM.

This analysis clearly indicated that the AAV-RGD viral particles bound $\alpha_v\beta_3$ integrin. The unmodified viral particles bound only at background level at all concentrations tested.

Example 9

The insertion of the RGD peptide in the capsid protein of AAV-RGD vectors modified the cellular tropism of these vectors. The cell entry pathway of the AAV RGD vectors was investigated by measuring gene transfer to cell lines expressing various levels of HSPG as well as intergrins $\alpha_v\beta_3$ and $\alpha_v\beta_5$. The following cell lines were tested: Hela cells, K562 human chronic myelogenous leukemia cells and Raji human lymphoblast-like cells..

First, flow cytometry was used to analyze the integrin and HSPG expression profile of these cell lines. Briefly, the cells were resuspended in SM buffer (HEPES-buffered saline containing 1% bovine serum albumin) at 2 x 10^6 cell/ml. The cells were incubated briefly at 37°C to allow regeneration of surface integrins, then incubated with FITC-labeled LM609 antibody or FITC-labeled PIF6 antibody (1:200 dilution, Chemicon, Temeula, CA) for two hours at 4°C. HSPG expression in these cells was analyzed with anti-HSPG monoclonal antibody, HepSS-1 (1:200 dilution) for two hours at 4°C. Subsequently the cells were washed five times with SM buffer and incubated with FITC labeled goat anti-mouse IgM serum (1:800 dilution) for one hour at 4°C, the cells were washed with SM buffer and analyzed by flow cytometry. This analysis demonstrated that Hela cells expressed high levels of HSPG and $\alpha_v\beta_5$ integrin and low levels of $\alpha_v\beta_3$ integrin. K562 cells expressed low levels of HSPG, but $\alpha_v\beta_5$ integrin was expressed at high levels. Raji cells were negative for HSPG expression and expressed high levels of $\alpha_v\beta_3$ and $\alpha_v\beta_5$ integrins. Subsequently, the ability of the wild-type AAV-eGFP and the modified vectors (A584-RGD4C-eGFP, A584-RGD4CALS-eGFP, A588-RGD4C-eGFP, A588-RGD4CGLS) to transfer the eGFP gene to Hela, Raji and K562 cells was analyzed. The cells were seeded in a 24-well plates the day prior to infection in order to reach 75% confluence or about 5 x 10^5 cell/ml on the following day. Serial dilutions of the vectors were added to the cells in the presence of Ad5 at the MOI of 3iu/cell. The cells and viruses were incubated at 37°C for 48 hours, after which the media was removed and the cells washed two time with PBS. The cells were then fixed and analyzed for GFP transduction by FACS analysis using an anti-GFP antibody.

Due to the low expression of HSPG, K562 and Raji cells were poorly transduced by AAVeGFP vectors containing unmodified AAV capsid protein, but

these cells were efficiently transduced by the same vector packaged into A5884C-RGD capsids. The efficiency of eGFP gene transduction by the A5884C-RGD vector was similar to that observed by the unmodified AAV vector in Hela cells. Furthermore, gene transfer mediated by the RGD-containing particles was 4-fold higher in the K562 cells and 13-fold higher in the Raji cells as compared to transduction by vectors comprising unmodified capsids. These experiments clearly demonstrate that incorporation of the 4C-RGD epitope into the VP3 monomer of AAV2 vectors resulted in dramatic changes in the initial steps of virus-cell interaction, presumably by creating an alternative cell attachment and entry pathway.

Experiments were also carried out to compare the binding profiles of the wild type AAV2 vector and that containing the 4C-RGD capsid protein using soluble heparin sulfate to compete for binding, and anti-AAV monoclonal antibody A20 and FACS analysis to detect binding. In these experiments, wild type AAV2 vector did not bind to Hela cells in the presence of heparin sulfate. However, vectors containing A5884C-RGD capsid protein bound to Hela cells in the presence of soluble heparin sulfate. Binding of modified AAV viral particles to Hela cells was blocked by treatment with synthetic RGD peptide. Since the RGD peptides could efficiently block binding, these data further suggest that AAV-RGD capsids use cellular integrins as receptors during the cell attachment process.

Example 10

Experiments were carried out to determine if the AAV-RGD vectors were capable of mediating gene delivery via integrin receptors.

Competitive inhibition assays using soluble heparin sulfate to inhibit AAV-mediated gene delivery were carried out as follows. AAV-RGD vectors or control vector AAVeGFP and modified vectors A584-RGD4C-eGFP, A584-RGD4CALS-eGFP, A588-RGD4C-eGFP, A588-RGD4CGLS were first incubated with 1500 μg/ml soluble heparin sulfate for two hours at 37°C and then incubated with the Hela cells at 4°C in the presence of 500 μg/ml heparin sulfate for an additional four hours. The cells were subsequently washed three times with fresh medium to remove unbound vector and incubated for 48 hours at 37°C, after which the cells were washed two

times with PBS, fixed and analyzed for GFP gene transduction by FACS analysis in Hela cells.

When infected with the control virus, AAVeGFP comprising the unmodified capsid, GFP gene expression in Hela cells was efficiently blocked by soluble heparin sulfate. The same concentrations of heparin sulfate only blocked about 20% of A5884C-RGD capsid-mediated GFP expression in Hela cells. These experiments further demonstrated that the A5884-RGD capsids were capable of using an alternative HSPG-independent cell entry pathway.

To assess the specificity of the alternate cell entry pathway through integrin receptor, synthetic RGD peptide (200 μg/ml) or anti-integrin antibody VNR139 was used to determine if AAV-RGD mediated gene-transduction was inhibited in the presence of soluble heparin sulfate. The addition of the RGD specific inhibitor in combination with heparin sulfate completely inhibited A5884C-RGD-mediated gene expression. This experiment demonstrated that the HSPG-independent interaction was due to interaction with RGD-binding integrins expressed on the Hela cells.

Example 11

The ability of unmodified AAV vector (wild type) to mediate GFP gene transduction was tested in various ovarian adenocarcinoma cell lines. Transduction of the eGFP gene was measured by FACS. Unmodified AAV vector mediated gene transfer and expression in the human ovarian adenocarcinoma cell lines PA-1, OVCAR-3, OVCAR-3N and OV4. Unmodified AAV vector did not transduce the ovarian adenocarcinoma cell lines Hey, SKOV-3 and OV3. The unmodified AAV vector transfers the eGFP gene via the HSPG receptor. HSPG expression in ovarian cancer cells was determined by FACS analysis using an anti-HSGP antibody (Seikagaku America, Falmouth, MA). The unmodified AAV vector was unable to transduce the Hey and OV3 cell line since these cell lines were negative for HSPG expression. See Table 8.

Since some human ovarian adenocarcinoma cell lines do not express HSPG, it was of interest to determine if ovarian tumor antigens (*e.g.*, integrin) would facilitate AAV-mediated gene transfer in ovarian cancer cells. Integrin expression was

analyzed by FACS analysis using an anti-α_v antibody and the data is displayed in Table 9. All ovarian cancer cells tested expressed a member of the α_v integrin family.

Table 9

Integrin and HSPG Expression on Human Ovarian Adenocarcinoma

Ovarian Adenocarcinoma	HSPG Expression	α_v Integrin Expression
PA-1	+	+
Hey	-	+
OVCAR-3	+	+
OVCAR-3N	+	+
OV4	+	+
SKOV-3ip	-	+
OV3	-	+

The AAV-RGD vectors A588-RGD4C-eGFP and A588-RGD4CGLS were tested for their ability to target gene transfer to the ovarian cell lines as described in Example 9. These AAV-RGD vectors were able to transduce all ovarian cancer cell lines tested. The AAV-RGD vectors were able to more efficiently direct gene transfer in the ovarian cell lines PA-1, Hey, OVCAR-3, OVCAR-3N, OV4, SKOV-3ip and OV3 in comparison compared to wild-type AAV vector containing unmodified capsid.

AAV-RGD mediated gene transfer was demonstrated to be independent of HSPG interaction. Competitive gene transfer experiments in the OVCAR-3 cell line were carried out with soluble heparin sulfate as described in Example 10. A5884C-RGD vector efficiently directed gene transfer in the presence of soluble heparin sulfate in OVCAR-3 cells. However, gene transfer was completely blocked by the addition of RGD peptide or anti-integrin antibody in the presence of soluble heparin sulfate. The A5884C-RGD mediated gene transfer proceeded through integrin receptors.

Example 12

Side-by-side comparison of the effectiveness of the unmodified AAV2 vector and the RGD-AAV vector for gene transfer to ovarian tumors was carried out *in vivo*. Human SKOV-3 cells were delivered intraperitoneally into SKID mice and developed tumors in the peritoneal cavity five days after implantation. The tumors were allowed to develop for five-seven days. Subsequently, matched doses of AAV-RGD vector or unmodified AAV vectors engineered to express the eGFP gene were administered intraperitoneally to the mice at 5 x 10^8 particles/mouse. At 15, 25, and 35 days post vector administration, the mice were sacrificed and the tumors were analyzed for the extent of gene delivery and expression. eGFP expression was detected in paraffin sections of tumor tissue using an anti-GFP antibody. In Table 10, GFP gene expression is indicated as a percent of tumor tissue expressing the gene, AAV-RGD indicates tumor tissue harvested from mice treated with AAV-RGD vector and ACG indicates tumor tissue harvested from mice treated with wild type vector.

Table 10

Day	GFP Expression	
	AAV-RGD	ACG
15	15%	3%
25	60%	7%
35	95%	7%

It is generally accepted that for an anti-tumor gene therapy to be effective a genetic vector must be able to deliver and express a gene in as much of the tumor as possible. In studies with other transgenes, (*e.g.*, HSV-TK) it has been established that at least 10-15% of the tumor needs to be transduced in order to be effective. This experiment suggest that the unmodified AAV2-vectors would not be effective anti-tumor agents since the transduction rate *in vivo* was low. In contrast, the modified RGD-AAV vector had a high rate of gene transduction and therefore may an excellent candidate for anti-tumor therapy. The fact that the eGFP expression comes

on slowly (increasing over a 5 week period) is not unexpected and is a characteristic of rAAV.

Example 13

In addition to inserting peptide ligands into the AAV2 vector to modify viral tropism, peptide insertions in the AAV2 vector can also be used as substrates for an enzymatic reaction covalently linking a biotin molecule in a site-specific manner to the AAV capsid. AAV capsids have been engineered to include a unique fifteen amino acid long biotin acceptor (BAP) peptide that is recognized by an *E. coli* enzyme, biotin protein ligase. In the presence of ATP, the ligase specifically attaches biotin to the lysine residue in this sequence. When the bacterial enzyme was expressed in a packaging cell line where AAV vector biosynthesis was occurring, vector capsid proteins were biotinylated as they were made and assembled into viral particles. The result of such a packaging scheme was *in vivo* biotinylated AAV particles. The advantages to labeling the AAV vector by biotinylation is that the reaction is enzymatic and therefore the conditions are gentle and the labeling is highly specific.

The AAV-BAP vectors were generated by methods similar to those described for the AAV-BPV, AAV-LH and AAV-RGD vectors in Example 1. Six AAV-mutants were generated and the packaging plasmids encoding these mutants are designated herein as pAB139BAP/ALS, pAB139BAP/GLS, pAB161BAP/ALS, pAB161BAP/GLS, pAB584BAP/GLS, and pAB584BAP/ALS. These mutants contain BAP insertions of the peptide sequence (GLNDIFEAQKIEWHE; SEQ ID NO: 11) flanked by either TG–ALS, or TG–GLS linker sequence (SEQ ID NO: 7 and 9, respectively). BAP insertions within the AAV vector following amino acids at positions 139 and 161 (regardless of the linker sequence) produced infectious mutant AAV vector particles at a level similar to wild-type. Insertion of the BAP peptide following amino acid 584 with the GLS linker causes a slight, but insignificant (less than 10-fold), decease in particle titer. Insertion of the BAP peptide at the same site within the AAV vector with the ALS linker caused a significant (>10,00 fold) decrease particle titer. All of the insertion sites within the AAV vector contemplated

by the present invention (positions 139 and 161 in the VP1/VP2 region and positions 459, 584, 588 and 657) are candidate sites for the BAP insertion.

Example 14

In order to label the AAV particles containing the BAP insert with biotin, a system for expressing the biotin ligase (*BirA*) enzyme in a packaging cell line was developed to create an *in vivo* biotinylated AAV vector. The *BirA* gene was inserted into the pCMV plasmid and is designated herein as pCMV-BirA. This plasmid was used to direct *BirA* gene expression in 283 cells and used with the AAV-BAP vector to produce *in vivo* biotinylated AAV vector. Briefly, 293 cells were transfected with the pCMV-BirA plasmid with a selectable maker gene (Neo). The resulting packaging cell was stably transfected with a rAAV comprising a DNA of interest flanked by AAV inverted terminal repeats, an AAV helper construct containing cap gene with a mutant BAP insertion (Example 12), an adenovirus helper plasmid or infected with adenovirus. Alternatively, 293 cells (which are standard AAV vector packaging cells) stably transfected with pCMV-BirA may be used as the packaging cell line. In addition, 293 cells infected with the adenovirus engineered to express the *BirA* gene may be used as the packaging cell line. AAV particles containing capsids with BAP insertions can also be labeled *in vitro* (post-purification) using purified BirA enzyme (available commercially).

Alternatively, a recombinant replication-competent adenovirus that expresses BirA was also developed for biotinylated AAV vector synthesis, eliminating the need for a separate *BirA* expression plasmid. This system allowed for large-scale AAV vector production of the biotinylated AAV utilizing packaging cell lines that have integrated copies of both AAV vector and AAV helper sequences. The Ad-based BirA expression system also was able to drive the expression of much larger amounts of the BirA gene product. The adenovirus expressed a BirA-eGFP fusion protein from a CMV promoter in the Ad E3 region, which allowed for monitoring BirA expression via GFP fluorescence.

A sensitive ELISA assay was used to quantitate the extent and efficiency of *in vivo* (and/or *in vitro*) biotinylation. AAV containing the 584BAP/GLS insertion was shown to be efficiently biotinylated *in vivo* (and *in vitro*) using either the plasmid

based or Ad-based BirA expression systems. The biotinylated AAV vectors when conjugated to biotinylated ligands (*e.g.*, monoclonal antibodies) via strepavidin can be specifically targeted to cell surface receptors of interest.

The advantages of using the biotinylation reaction to label the AAV viral particles is that it is an enzymatic reaction and therefore the conditions are gentle while the labeling is highly specific. In addition, the *in vivo* biotinylation reaction described herein has a much higher biotinylation efficiency than chemical biotinylation utilizing cross-linking reagents.

The biotinylated AAV viral particles are contemplated to serve as substrates for conjugation of targeting motifs(*e.g.*, monoclonal antibodies, growth factors, cytokines) to the surface of vector particles through utilizing avidin/strepavidin-biotin chemistry. In addition, the biotinylated AAV viral particles are contemplated to be useful for visualizing the biodistribution of the viral particles both *in vivo* and *in vitro*. The biotinylated viral particles can be visualized with fluorescence or enzymatically with labeled strepavidin compounds. Biotinylation may also be useful for conjugating epitope shielding moieties, such as polyethylene glycol, to the AAV vector. The conjugation of shielding moieties will allow the vector to evade immune recognition. Biotinylation of the AAV vector is also contemplated to enhance intracellular trafficking of viral particles through conjugation of proteins or peptides such as nuclear transport proteins. Biotinylation may also be use to conjugate proteins or peptides which effect the processing of AAV vector genomes such as increasing the efficiency of integration. In addition, biotinylation may also be used to conjugate proteins or peptides that effect the target cells, *e.g.*, proteins that make a target cell more susceptible to infection or proteins that activate a target cell thereby making it a better target for the expression of a therapeutic or antigenic peptide.

While the present invention has been described in terms of preferred embodiments, it understood that variations and improvements will occur to those skilled in the art. Therefore, only such limitations as appear in the claims should be placed on the invention.